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Abstract. *Non-destructive measurement of crop growth stage, canopy development, and height may be useful for more efficient crop management practices. In this study, ultrasonic sensing technology was investigated as one approach for corn plant canopy characterization. Ultrasonic echo signals from corn plant canopies were collected using a lab-based sensor platform. Echo signal peak features were extracted from multiple scans of plant canopies. These features included peak amplitude, scan number, and time of flight. Feature vectors with similarities were clustered together to identify individual leaves of the canopy. The mean height of the clustered data of individual leaves was estimated. The growth stage of each plant was estimated based on the number of leaves detected. Regression analysis was used to describe the relationship between manually measured leaf heights and ultrasonic estimates. A leaf-signal interaction model was developed to predict which* *parts of leaf surfaces will result in echo signals detectable by the sensor. The aim of this research was to develop a sensing system which extracted information from an ultrasonic sensor that could be used for a variety of sensing operations in precision agriculture and to better understand the relationship between corn plant canopy and ultrasonic signals.*

Keywords. Corn, ultrasonic, precision agriculture, plant canopy

Introduction

Precision agriculture is a comprehensive system designed to optimize agricultural production through the application of crop information, advanced technology, and management practices. While much of the technology is in place to implement precision agriculture, like yield monitoring and variable rate application control, much is to be learned about the interactions between sources of variability in field (Johnson and Raun, 2000). Kaspar et al. (2004) determined the relationship between terrain attributes and corn yield and found that higher and more sloping field positions would have less water infiltration and lower yields. In preliminary work, manually corn collar height measured at the V3 growth stage was somewhat correlated with yield and showed potential to be an indicator of nitrogen response along a transect (Kaspar, unpublished data). If an automated, non-destructive crop growth stage, canopy development, and height sensing system could be developed, it may able to characterized crop growth variability across a landscape. Better landscape characterization may be useful in determining what site-specific inputs a crop requires while reducing risk to the environment and optimizing production outputs.

Ultrasonic sensing is a technology that has potential for non-destructive crop canopy characterization. Ultrasonic techniques have been used in the past for agricultural applications based on the basic idea of distance measurement. Distance is determined by transmitting a burst of high-frequency sound, then waiting for the echo to return from surfaces within the sensor field of view. The distance can then be computed based upon the speed of the sound and the elapsed time between sound transmission and echo return (Ciarcia, 1984).

Ultrasonic sensing has been investigated for crop sensing applications. Sudduth et al. (1998) compared two methods, ultrasonic and GPS measurement of combine swath width and found that ultrasonic sensors are relatively less expensive and could provide a direct measurement of swath width without the extensive data processing required by the GPS-based method. Kataoka et al. (2002) showed that an ultrasonic sensor had good performance for soybean and corn height measurement compared to laser beam sensor. In their study, both sensors were vertically attached to the front head of a sprayer which was driven along the crop row to measure the changes of vertical distance between sensor and plant canopy. They found that ultrasonic sensor measured data followed the changes of the plant canopy height, while the laser beam sensor seemed to be too sensitive and did not give good correlation with height measurements. Shibayama et al. (1985) developed an ultrasonic pulse wave transceiver that was sensitive to canopy structural differences and concluded that ultrasonic pulses are especially sensitive to horizontal components in plant canopies. The major components detected by this system were the horizontally oriented leaves. Other components like ears could reflect the sound if they had components perpendicular to the direction of sound. Sui et al. (1989) developed a microcomputer-based measurement system using ultrasonic ranging modules to provide accurate and consistent estimates of cumulative plant volume, maximum and average plant width and height for a variety of bush-type plants such as cotton and soybean.

In previous work, Shrestha et al. (2002) investigated ultrasonic estimates of corn plant height in a lab environment using an ultrasonic sensor which mounted above and perpendicular to plant canopy. The distance to the plant canopy was measured by detecting the time delay of ultrasonic echoes and collar height of the plant was estimated. They found that the estimated height had a good correlation with the manually measured height.

The aim of this research was to develop a sensing system utilizing ultrasonic sensor information for corn plant canopy characterization that could be used for a variety of sensing operations in precision agriculture. In particular, the specific objectives of this research were to (1) develop signal processing techniques for ultrasonic sensor signals to estimate the heights of individual leaves and plant growth stage, and (2) develop a model describing the relationship between corn leaf and reflected ultrasonic signals.

Methodology

Experimental Design

Ultrasonic echo signals from corn plant canopies were collected using a lab-based sensor platform consisted of a motion control system on which an ultrasonic sensor (Model M-5000/95, Massa Products, Hingham, MA) was mounted above and perpendicular to the soil surface. The sensor was moved in the horizontal plane using a lead screw and a PK 2110 (Z-World, Davis, CA) single-board computer with a 6.144 MHz microcontroller was used to control the motion of the sensor. This sensor was designed to sense depth in a range between 0.3 and 4.0 m. Two sets of 10 corn plants at V6 and V9 growth stages respectively were placed on the imaging stage one plant at a time and scanned with the ultrasonic sensor. The ultrasonic sensor was passed over the individual plants at a velocity of 0.57 cm/s. The echo monitor output signal from this sensor was connected to a data acquisition system (DaqBook/120, IOTech, Cleveland, OH). The signal was a diagnostic output that includes the transmit pulse and the reflected signals from the target. An oscilloscope was used to observe the signals during collection. Air temperature at scanning was recorded and ranged between 27 and 29 degrees C. Manual measurements were taken of corn plant collar heights, maximum plant heights, and maximum height of each leaf. Digital still photos were taken of each plant for future reference.

Procedure

The signal resulting from reflections from the target was an analog voltage ranging from 2.4 V to 5.3 V. The data acquisition system sampled this signal at 100 kHz and acquired 1400 samples of the peak detection signal voltage for each scan. Ultrasonic pulses were launched at a frequency of 2 Hz, and the frequency of the ultrasonic waveform was 95 kHz. Depending on the top projected canopy area of a plant, between 252 to 360 scans were acquired of individual plants as the sensor was passed over the plant canopy at a speed of 0.57 cm/s. For this lab-based environment, this speed was appropriate for the sensor to adequately characterize the plant canopies.

Ultrasonic signal processing was done with MatLab script language (Version 6.1, The MathWorks, Natick, MA). Signals were filtered using a low pass filter which had a cutoff frequency of 0.2 Hz to minimize the effect of noise.

Two aspects of ultrasonic sensing were investigated. First, the heights of corn plant leaves were estimated using ultrasonics echo signals and subsequent signal processing. Second, the interaction between between corn leaf surfaces and ultrasonic signals was investigated to better understand which surfaces could be expect to return a signal to the sensor.

Leaf Height Estimation

Ultrasonic signals were processed to find the start of echoes that were reflected back from the object in the sensor field of view (FOV) using fixed threshold at 2.7V. Time of flight of each detected peak was converted into a height estimate using the equation:

$$\mathrm{H} = \frac{L - ct\sqrt{T + 273}}{2} \tag{1}$$

where

L is the distance between ultrasonic sensor to the ground, 2.105 m,

c is speed of sound in air, 20.064 m/s,

t is the round-trip time of flight, s and

T is the air temperature in degrees C.

For each echo peak, a peak feature vector composed of features such as time of flight, height and scan number was calculated. Peak feature vectors were clustered together according to height similarity and scan number to identify individual leaves of the corn plant. Then the mean height of the clustered data of individual leaves was estimated. The growth stage of each plant was estimated based on the number of leaves detected. Regression analysis was used to describe the relationship between manually measured leaf heights and estimates from ultrasonic measurements.

Leaf-Signal Interactions

Shibayama et al. (1985) observed that the relative frequency of detected echo peaks was a function of leaf angle as well as other parameters such as leaf area, leaf density and leaf height. The interaction between leaf angle and ultrasonic signals was investigated based on the basic principles of sound wave propagation and reflection. A sound beam incident upon a reflective surface will be reflected at an angle equal to the incident angle (GBSB, 1996; Figure 1).

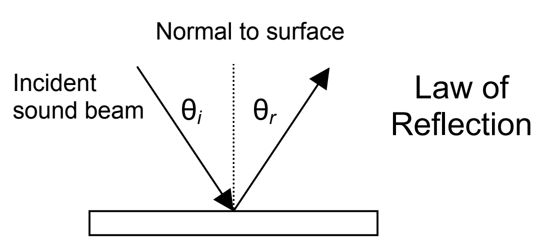


Figure 1 The law of reflection states that reflection angle, θ_r *f*or a beam incident upon a reflective surface is equal to the incident angle θ_i.

The beam angle of the ultrasonic sensor used in this study was +/- 4˚. Based on the wave reflection principles, those sound waves which would be detected by the sensor would propagate from the sensor in a cone whose size was determined by the beam angle. When the wave comes in contact with the leaf surface, a portion of the sound energy is reflected from the leaf surface. In order for the reflected wave to be detected by the sensor, the surface must be oriented so that the wave is reflected back to the sensor within the beam angle. Thus prototype leaf models with simple mathematical forms were developed. The tangent line along a leaf surface model was calculated where the slope of the tangent line is the derivative of the leaf model function, y (Figure 2). Using this tangent line, the tangent angle θ_0 relative to the horizonal at (x_o, y_o) point was calculated using the equation:

$$\theta_0 = \tan^{-1}\left(\frac{dy}{dx}\right)\Big|_{x=x_0} \quad (2)$$

Since the beam angle of the sensor is 4˚, any point on the surface that has a tangent angle, θ less than 4˚ would reflect back the signal to the sensor receiver (Figure 2). Using this model, we determined the regions of prototype leaf surfaces that would produce detectable echos by the sensor.

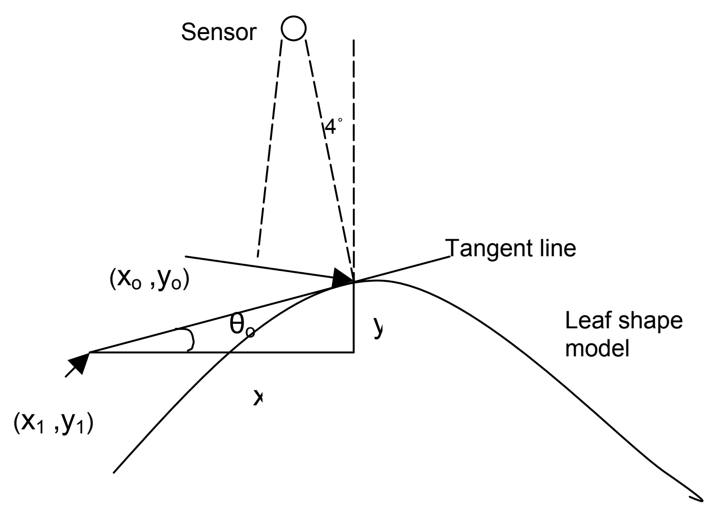
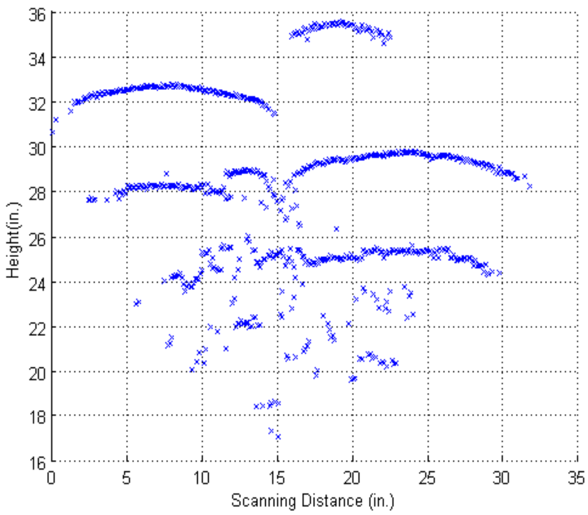


Figure 2 Tangent line of a leaf surface at point (x_o,y_o)

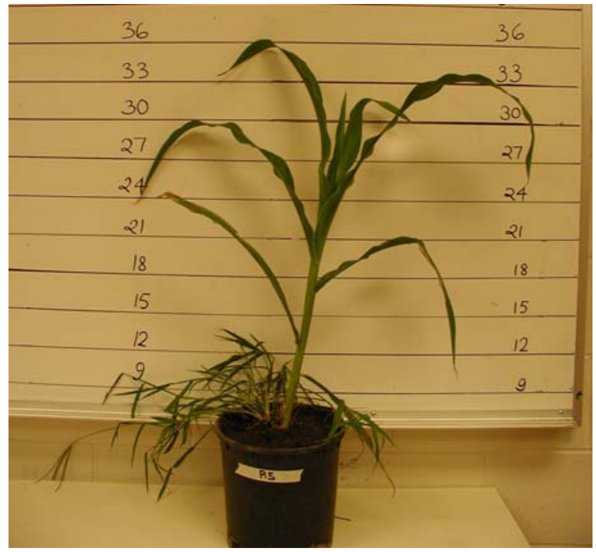
Results and Discussion

Leaf Height Estimation

Detected echo peaks were converted into estimated height and plotted against the scan number (Figure 3). In many cases, the number of visible leaves and their heights can be observed. The leaf shapes in the scatter plot were more flat than the original plant because we received multiple reflected signals from the same point due to the large FOV of the sensor. Erect leaves were not detected by the ultrasonic sensor because these leaves reflected the ultrasonic signal away from the sensor. Leaves in the whorl tend to be more erect, so they tended to not reflect the signal back to the sensor. Echoes were only detected if the leaves bent enough to be roughly perpendicular to the sensor. Leaves that were fully extended tended to be more perpendicular to the sensor and appeared in many scans and were typically identifiable as distinct leaves.



(a)



(b)

Figure 3. (a) Example scatter plot of leaf height estimates from ultrasonic scans as a corn plant in photo (b) was scanned from left to right.

Other echoes after the first received echo may also be present. These may be due to the sound bouncing off multiple reflectors and back to the transducers, or echoes from targets beyond the first target.

The height measurements of individual leaves using the ultrasonic sensing system for 18 plants were generally correlated with the manually measured heights with r^2 =0.56 (Figure 4). Data from two V6 growth stage plants were removed as outliers because of unreasonable height scale due to bad condition of plant or error in lab experiment and data collection. Figure 5 shows the regression line of leaves height from eight V6 growth stage plants with r^2 = 0.87. For the V9 growth stage, estimated individual leaves height from all 10 plants were regressed onto actual leaves height and the correlation of determination, r^2, was 0.41 (Figure 6).

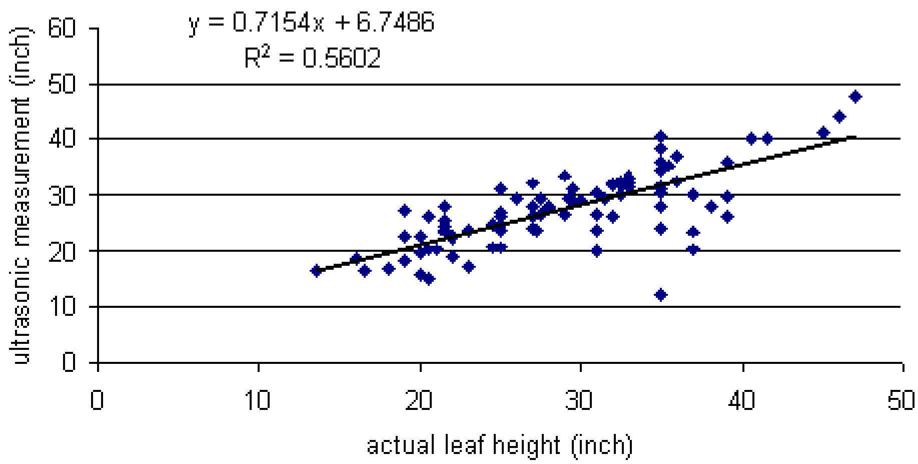


Figure 4. Estimated individual leaves heights regressed onto manually measured leaves height for 18 plants.

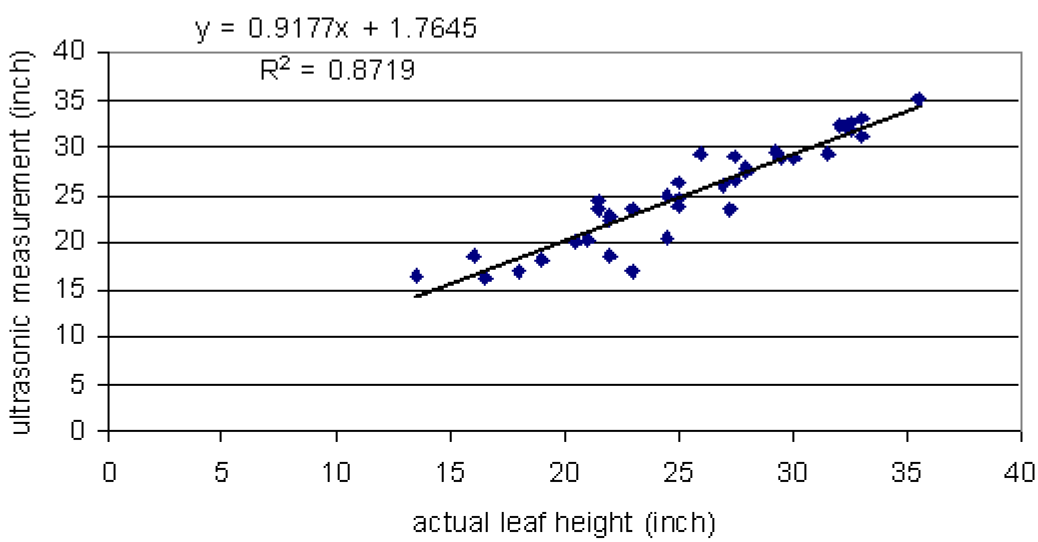


Figure 5. Estimated individual leaves heights regressed onto manually measured leaves height for 8 plants of V6 growth stage.

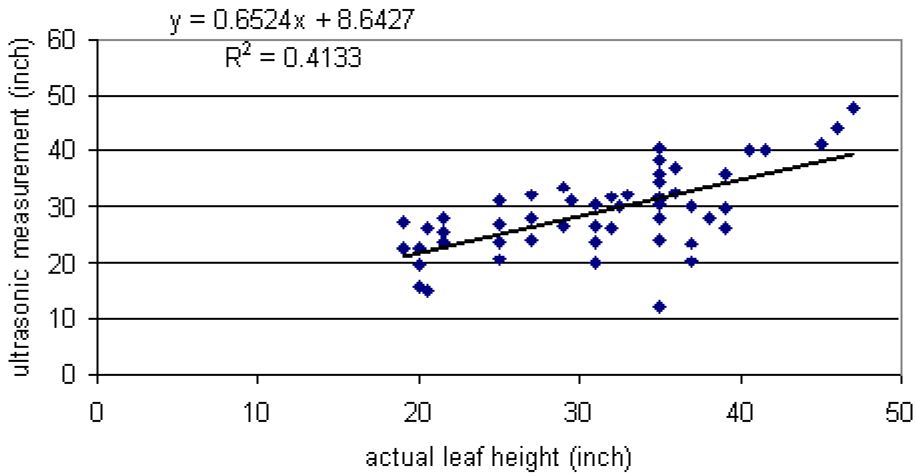
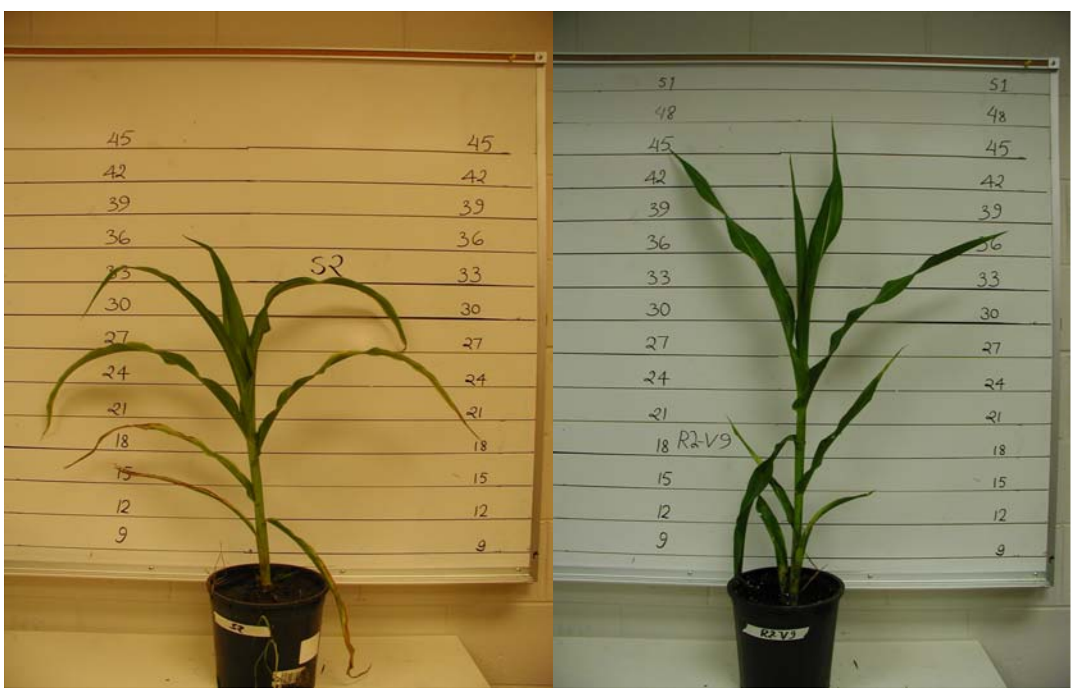


Figure 6. Estimated individual leaves heights regressed onto manually measured leaves height for 10 plants of V9 growth stage.

The leaf height estimates of the V9 growth stage plants were less correlated because the later growth stage tended to have longer and more erect leaves which resulted in fewer detected echoes. Moreover, the individual leaf heights for the V9 growth stage plants were often measured at the tips of the leaves as in the measurement protocol the maximum height of individual leaves was measured. In the case of the V6 growth stage plants, the maximum height tended to be at the top of an arc made by the leaves which tended to be larger horizontal surfaces and thus produced echoes that were detectable by the sensor (Figure 7).



(a) (b)

Figure 7. Comparison of sample plant of (a) V6 growth stage and (b) V9 growth stage.

The growth stage of the corn plants for each set of plants was estimated by averaging the number of visible leaves detected by the ultrasonic sensor. The average number of leaves detected for the set of V6 growth stage plants was 6 leaves. For the set of V9 growth stage plants, the average number was 6.2 leaves. The number of leaves for the V9 growth stage was lower because lower leaves were often not present on the plant due to natural death or physically being torn from the stalk once a plant developed beyond the V5 stage. In addition, for the later growth stages, the lower leaves will tend to be more occluded by the upper leaves.

Leaf-Signal Interactions

As a theoretical development to better understand the interaction of the sensor with idealized models of plant leaves, two possible leaf shapes were modeled, a parabolic shape and a straight line at a slope shape. For a parabolic shape, the number of points detected as sensor traveling along a convex curve $y = mx^2$ are increasing exponentially as the m parameter increasing from -0.350 to 0. For a straight line at a slope shape, the ultrasonic signal will be reflected back to the sensor if the slope is less than 0.70 (Figure 8).

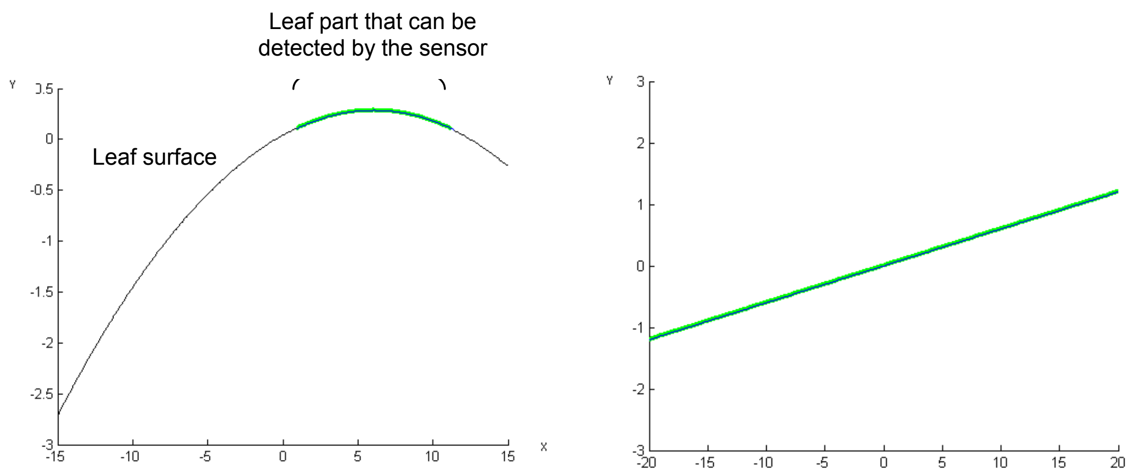


Figure 8. Two possible leaf shape models, (a) parabolic leaf shape and (b) straight line slope shape. For the parabolic leaf shape, only top surfaces were be detectable and for straight line at a slope shape, all part can be detected if the slope is less than 0.70.

Even though we have not yet developed a full model for the relationships described by Shibayama et al. (1985), leaf angle is a major factor affecting the echo peak distribution. More studies are needed to retrieve as better correlation between ultrasonic measurements and other useful plant characteristic in field crop studies such as collar height (Shrestha et al., 2002), cumulative leaf area index (LAI) and plant canopy density (Shibayama, et al., 1985). In this study, we only dealt with basic leaf plant model. However, full plant model development like that described by Prevot et al. (1991) may be useful to better understand the relationship between ultrasonic signal and spatial plant canopy characteristics.

This information is very useful in examining the expected ultrasonic signal that would reflected back to the receiver as the sensor scans through a plant canopy. With a full plant model, it may be possible to determine the correlation between the measurement of plant height using this mathematical modeling and actual manual measurements.

Conclusions

The estimates of individual leaf heights from ultrasonic measurements of individual leaves using the time of flight calculation method were positively correlated with manually measured heights. The r^2 of the regression line between estimated individual leaves heights and manually measured leaves height for 18 plants was 0.56. Estimation of the corn plant growth stage gave a good result for V6 growth stage. Estimates result for V9 growth stage was much lower due to leaf orientation, missing leaves, and leaf occlusion.

In summary, simple spatial characteristics of plant leaves in relation to their height, growth stage, and angular responses of ultrasonic reflection were investigated in this study. The insight derived from this work should have utility in the design of an ultrasonic sensing system for corn plant characterization.

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